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Case study

Flywheel starter ring gear failures and hardness variation reduction in surface hardening process

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ABSTRACT

In general technical applications, truck heavy duty engine flywheel starter ring gears teeth is conventionally induction hardened and tempered in order to meet metallurgical aspects on specification. Especially for large sectioned starter ring gears (in this case diameter of the gear is 470 mm) the critical issue is to maintain a stable hardness distribution on gear cross sections. These hardness variations in process could yield to:

1. High scrap costs due to out of specification parts.
2. Increase in tact time in process, decrease in labor efficiency due to scrap rate and excessive hardness measurements.
3. Potential risk of failure on engine in low mileages.
4. 100% hardness measurements in ongoing process which leads to time and cost waste.

This technical paper summarizes the case study conducted for truck flywheel starter ring gears with diameter of 470 mm in order to reduce hardness variation by optimization of induction hardening and tempering processes.

1. Introduction

Blank flywheel starter ring gears are supplied as normalized condition DIN Ck 45 steel with hardness range of 152–217 HB. The steel grade is designated as heat treatable plain carbon steel for engine components subjected to mild loads. The location of flywheel starter ring gears the gear in the engine is indicated in Fig. 1.

The chemical composition values are given with actual measurements of serial production flywheel starter ring gears in Table 1.

2. Process flow

Blank starter ring gears are machined and heat treated in flywheel machining line. General process map for truck flywheel starter gear machining process is shown in Fig. 2.

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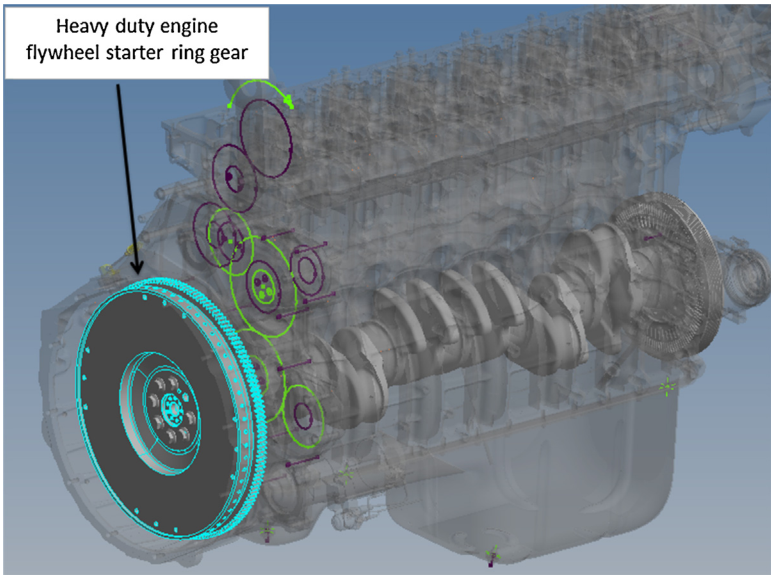

Fig. 1. The location of flywheel starter ring gears the gear in the engine.

Table 1
Chemical composition of flywheel starter ring gear.

Element	Lower limit	Upper limit	Measured on failed part	Status
%C	0.42	0.5	0.45	Okey
%Si	N/S	0.4	0.19	Okey
%Mn	0.5	0.8	0.67	Okey
%P	N/S	0.035	0.016	Okey
%S	N/S	0.035	0.008	Okey

N/S: Not specified.

At first process step; the blank gears are clamped for teeth hobbing process and teeth profile is machined in hobbing process.

After deburring, the starter gear is induction heated to austenitizing temperature by a coil designed according to the outer dimensions of ring gear and rapidly quenched in polymer based quenchant for martensitic transformation.

Subsequently, the hardened starter are loaded to thermocouple controlled tempering furnace as batches (30 parts/batch) for according to engineering specification requirement (48–56 HRC hardness) on surface tooth tip as specified in Fig. 3.

From the side of heat treatment process; the main technical difficulty leading to hardness variation is the dimensions of the (470 mm) starter gear where no significant hardness variation (within ±1.5 HRC) is observed on small section size flywheel starter gears on metallurgical controls. In this case, maintaining the hardness within the specification and without variation in 150 teeth is critical issue. The scope of the process is defined as "large section" truck flywheel starter gears.

These gears are 100% frequency hardness checked from circumferentially equally separated 8 teeth where 1/batch control frequency is commonly applied for gears as recommended on global heat treat standards.

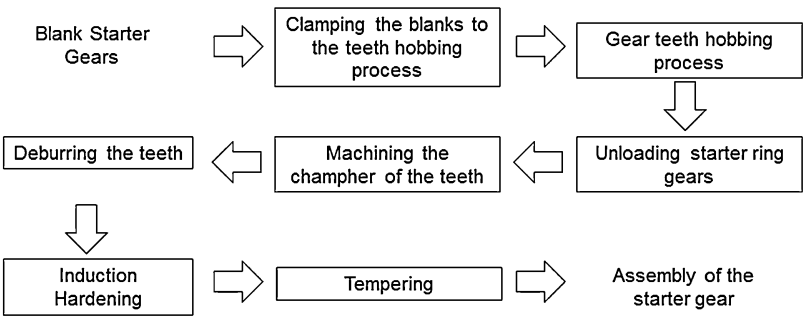

Fig. 2. General process flowchart for flywheel starter ring gear.

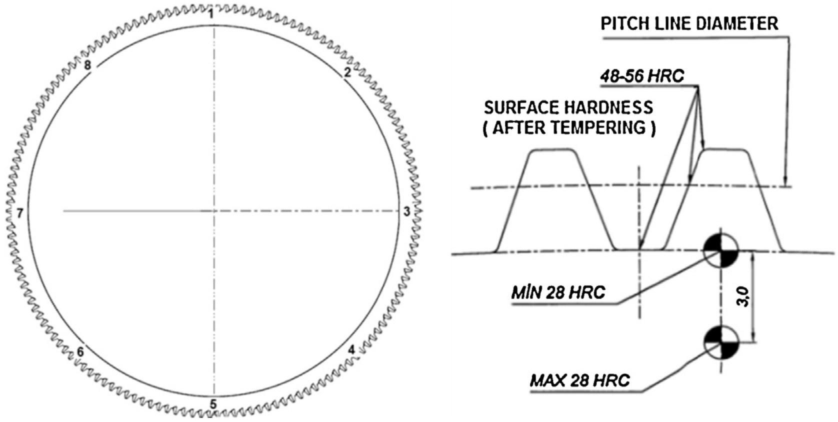

Fig. 3. Hardness specification on part drawing and measurement points on starter ring gear.

The anova analysis for hardness distribution of 30 gears taken from batch with 8 point measurement results are given in Fig. 7. As seen from boxplot data, there are points out of specification both on lower spec limit and upper spec limit with wide range of hardness variation. The main disadvantages are:

1. High scrap costs due to out of specification parts.
2. Deformation on gears due to hardness variation in different section on gear body.
3. Increase in tact time in process, decrease in labor efficiency due to scrap rate and excessive hardness measurements.
4. Potential risk of failure on engine in low mileages. A sample photo of failed starter ring gear is given in Fig. 4 (The fracture is in ductile nature where the surface hardness was measured as 58–61 HRC locally around failed tooth (spec is 48–56 HRC).
5. %100 frequency hardness percent hardness measurements from multiple points (minimum 8 measurement points) in ongoing process as an interim action leads to time and cost waste.

The main target of the study is to reduce teeth to teeth and part to part hardness variation on truck flywheel starter gears by minimum 40%. The methodology is defined on the next sections of this paper.

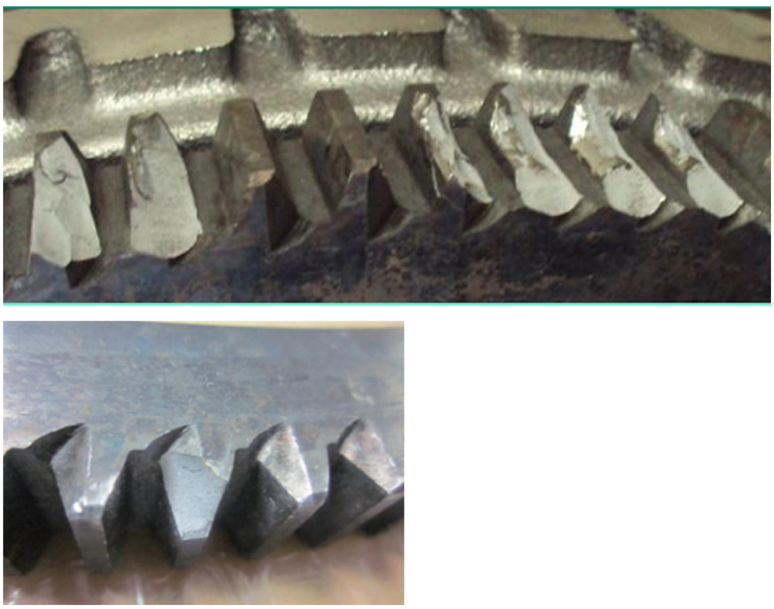

Fig. 4. Photo of failed truck starter ring gear.

3. Induction hardening and tempering process overviews

The study is focused on improving hardness induction hardening and tempering process. The process mainly depends on many process parameters by means of uniform hardness pattern. The factors effecting on the hardness variation is evaluated by the study team. The fishbone diagrams for potential root cause(s) are reported in Fig. 5.

Two items were selected by the team;

1. *Tempering: Part loading (batch) number and part location*: In tempering process of carbon & low alloy steels two main parameters are effective; tempering times/temperatures and furnace loading. A wide range of acceptable tempering temperatures and times can be selected to achieve final properties for a given steel alloy. In practice, tempering temperature has more dominant effect on tempered hardness than tempering time [3].

Furnace loading is another key parameter influencing the time–temperature profiles of furnace loads during heat-up to the desired temperature. Loading must consider the weight of the furnace load, as well as the load density. Baskets full of small parts might give the same overall furnace load density as a whole furnace filled with fewer larger parts, but the parts at the center of the basket will be somewhat insulated and will take longer to reach the proper temperature. Thus local load density as well as overall furnace load density must be considered [3].2. *Induction hardening: quenching:* The quenching system for induction hardening is defined by 8 parameters: heat time/scan rate, power level, power, frequency, part position/rotation, quenchant concentration, quenchant flow, quenchant temperature, and quenching time [2].

Important simultaneous changes of one or more of these parameters can produce unwanted effects on the workpiece, which, in extreme cases, result in an unsuitable microstructure, deviations in the depth of the hardened profile, unsuitable hardness variation (too low hardness, soft spots), and exceeding the distortion of the machine element [2].

Especially less hardenable alloys require more rapid cooling to obtain martensite. On the other hand, section size is an important consideration in quenching. As the section size increases, the alloy content of the steel and/or the quench severity must be increased to insure adequate quenching cooling rates [3]. In this case, when the plain carbon steel grade for general purpose heat treatment (DIN Ck45) with 470 mm complex section size is considered, the quenching is assessed as key point to reduce variation in hardness.

For verifying these factors, each of them are individually tried where the other factors (parameters) are not changed. These trials are described in following sections.

4. Tempering process – experimental studies

In current process, after induction hardening process tempering process is carried out in thermocouple controlled, sealed electrical furnace. Tempering process is carried out at 290 °C for 70 min. The parts are loaded to furnace by minimum

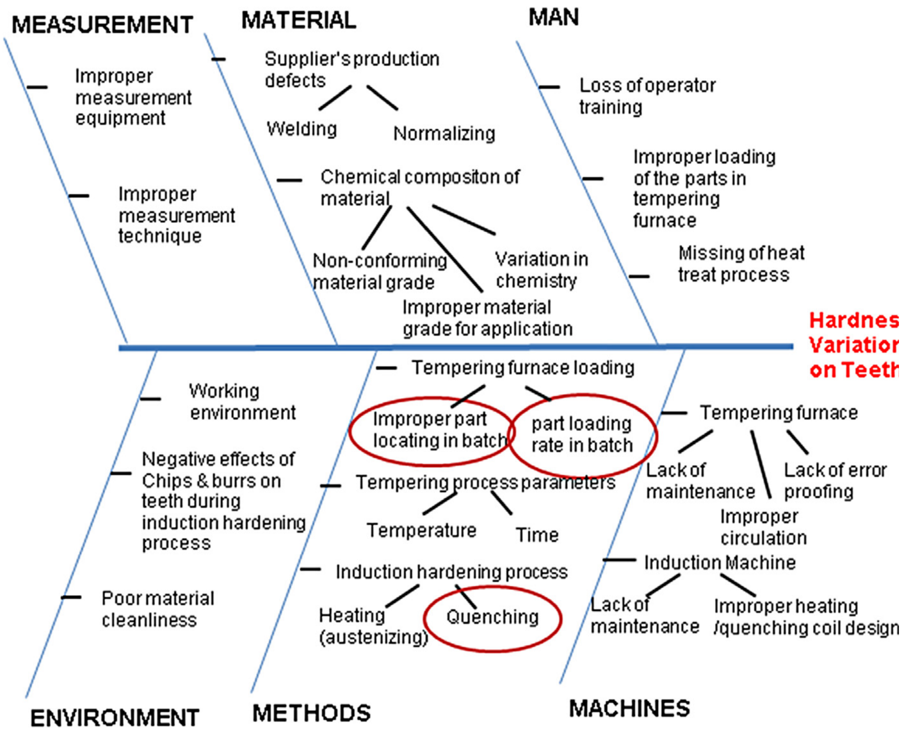

Fig. 5. Fishbone diagram for hardness variation of truck flywheel starter gear.

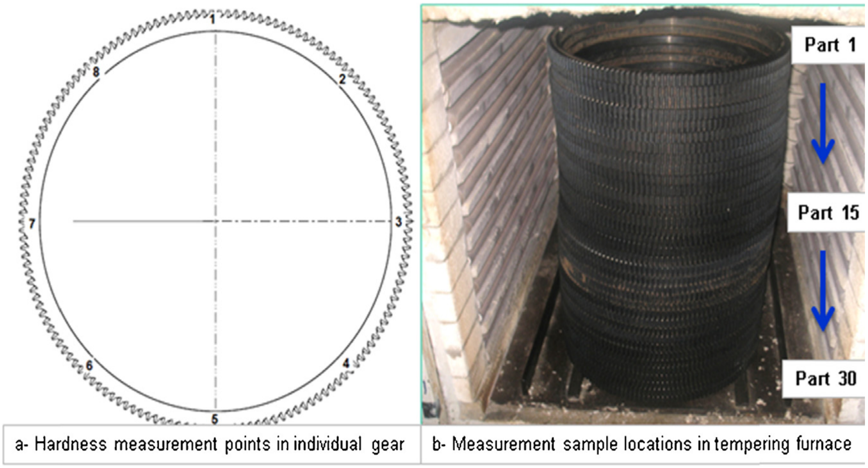

Fig. 6. Hardness measurement points (a) and part arrangement in current process with numbering (b).

30 truck flywheel ring starter gear batches. The gears are stacked on each other in batch. The tempering furnace and the arrangement of the truck flywheel ring starter gears are shown in Fig. 6b.

In order to analyze current hardness distribution in terms of teeth to teeth variation and part to part variation, all of the parts are numbered in terms of loading sequence and detailed hardness measurements from 8 different measurement points (Fig. 6a) are conducted. Anova analysis of hardness measurement results are reported as boxplot data in Fig. 7.

As a result, the truck flywheel starter gears loaded at bottom indicates (especially part numbers 24–30) lower hardness. On the other hand, the gears located at top side have higher surface hardness (especially part numbers 1–15).

This result indicates a restricted circulation (see schematic view in Fig. 9) leading to non-stable hardness distribution of the gears within the batch. Improvement actions are planned for improving circulation in the tempering furnace will be assessed in Section 6.

In addition to these findings, variations of hardness up to 14 HRC in individual gear is another issue to investigate to confirm hardness homogeneity of the ring gears after induction hardening process. Issue will be discussed in induction hardening process review title of this paper.

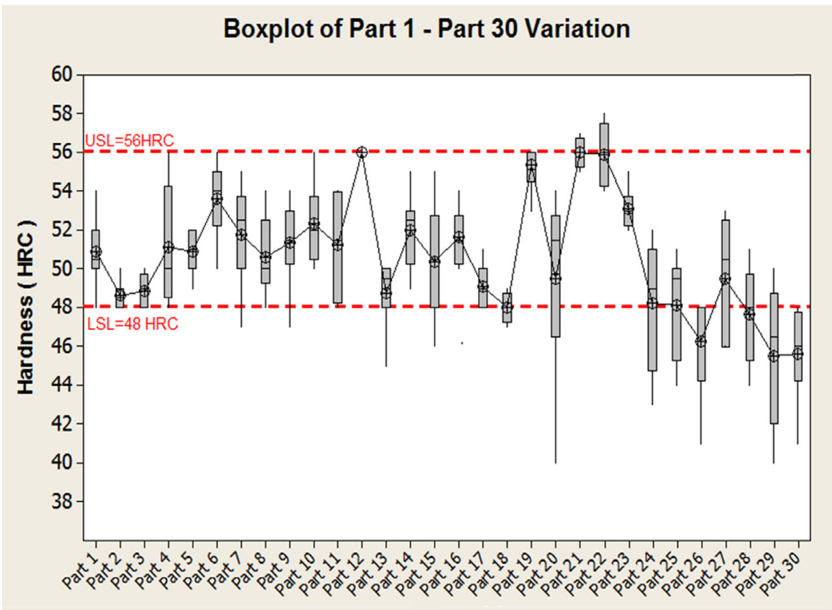

Fig. 7. Anova analysis for hardness distribution of the batch after tempering.

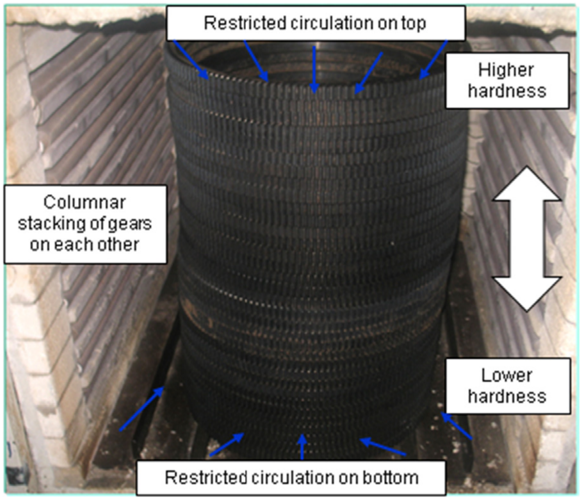

Fig. 8. Restricted circulation in columnar stacking of the truck flywheel ring gears in tempering furnace.

5. Induction hardening process – experimental studies

To harden a work piece, it must be heated up to between 30 and 50 °C above its upper critical temperature and than quenched in adequate medium which will produce desired rate of cooling on the workpiece.

The two most common types of quenching systems consist of spray quench rings and immersion techniques. When quench rings are used for round bars, their shape, like the coil, is generally round. The ring may be located concentric with the coil or directly underneath or alongside it as in single-shot induction hardening setups [1].

In this case, flywheel starter ring gears are quenched in spray quench rings on coil body as shown in Fig. 9. Induction hardening process in facility consists of two main stages:

1. The truck flywheel starter gear is located in rotational table in the coil. Part is heated to austenitizing temperature and hold for sufficient time for completely austenitizing (80 s). The current coil design is illustrated in Fig. 9.
2. After austenitizing the truck flywheel starter gear is dropped to the level of quenching ring which is located underneath the induction coil body. The quenching takes place with rotational table (60 s). Quenching medium is polymer quenchant with temperature control.

Adequate controls are necessary to ensure consistent results in induction heat treatment. Such controls for spray quenches include those for quenchant flow, temperature, timing, and so forth. Control of the temperature of the quenching medium and its timing are also important for uniformity [1].

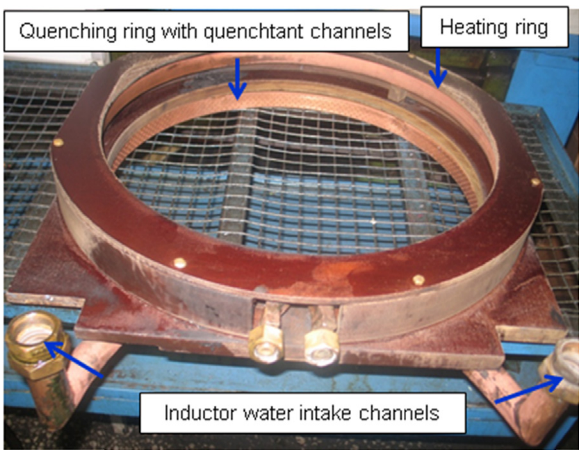

Fig. 9. The inductor coil for truck flywheel starter ring gear consists of heating ring and quenching rings inside.

In current process, trial is run to verify quenching efficiency in both spray quench rings and immersion techniques.

5.1. First step quenching trial for verification

As a first trial step for verification, process parameters are constant. The rotational turning of the flywheel starter gear is canceled to determine the quench efficiency of the inductor in different sections of the truck flywheel ring gear. For this purpose the truck ring gear and corresponding sections of the coil is marked and 3 part trials were run for verification.

The hardness distribution lay out for the trial is reported in Fig. 10. As a result, points without sufficient quench effect showed significantly low hardness values than lower spec limit of the specification. Individual sections with insufficient hardening (14–45 HRC) are indicated in red color in Fig. 8. Also, quite high teeth to teeth hardness variation up to 43 HRC is observed (where the spec is 48–56 HRC after tempering).

These results indicate quenchant restrictions to complete cross section of truck flywheel starter gear within 470 mm root diameter.

In addition to hardness metrics, visual observations are also conducted by canceling rotation of table to observe low hardness sections. Visual controls without rotating the part during quenching, less quenchant flow sections were matching with low hardness sections. This situation is related to insufficient quenching effect due to interference of quenchant jets during quenching.

5.2. Second step quenching trial for verification

As a second verification trial is planned to conduct such that quenching is done in externally established immersion tank manually to cross check the results with first step trial. To achieve this, the quench jets of the coil were canceled and the external quench tank with polymer quenchant established instead. In this trial, the ring gear is austenitizing in coil as routine procedure, but after austenitizing taken for immersion to the external manually circulated quench tank. The parts were hold in external quench tank for sufficient time (60 s) to ensure adequate quenching. The measurement results are reported in Fig. 11. The hardness measurement results are within teeth to teeth variation was reduced to max 3 HRC after this trial.

According to the results, the variation source is confirmed as quenching process. Improvement studies are planned in quench process to eliminate hardness variations at cross section of truck flywheel ring gears. The details will be assessed in improvement studies section of this paper.

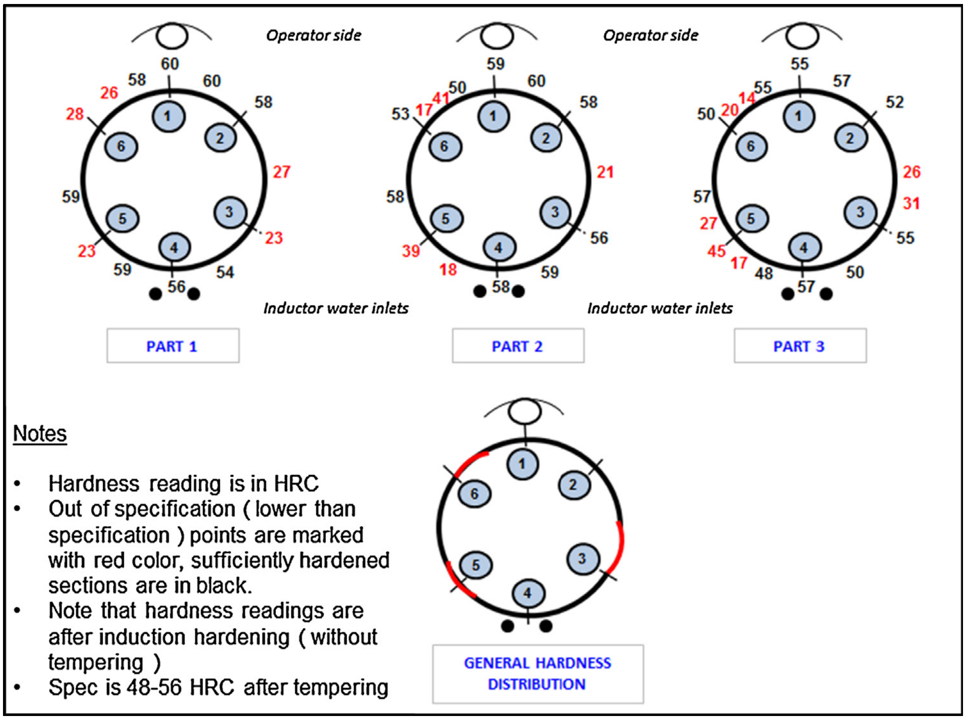

Fig. 10. Hardness distribution lay out of trial 1. The soft sections are indicated in red color. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

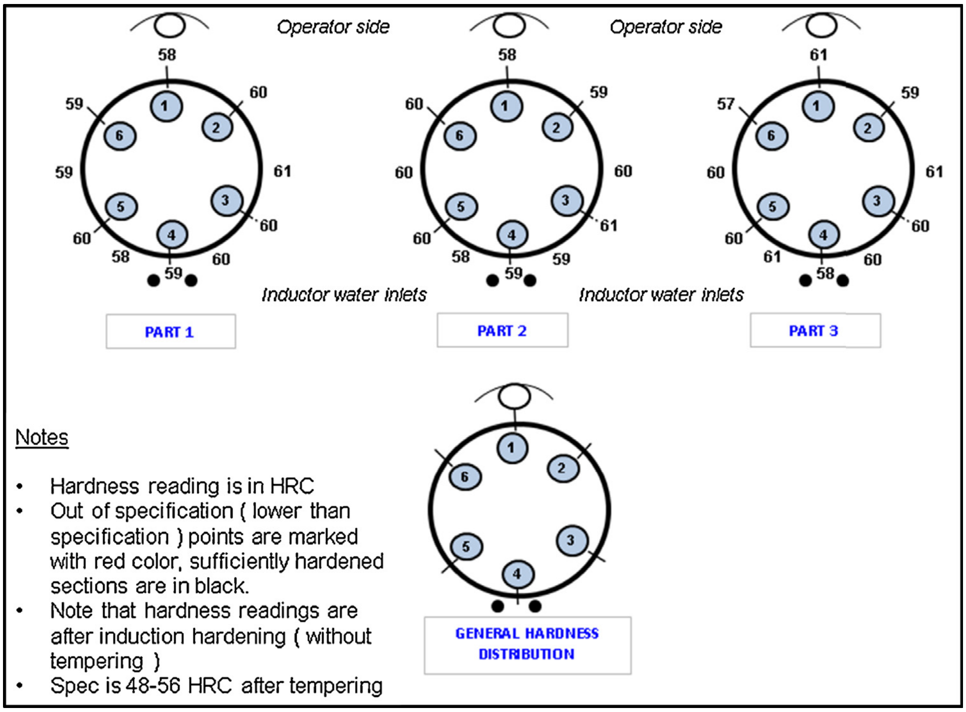

Fig. 11. Hardness distribution lay out of trial 2. No soft sections are observed with maximum 3 HRC teeth cross section hardness variation.

6. Improvement studies in induction hardening and tempering

As discussed earlier, two main improvement opportunities to reduce teeth to teeth and part to part hardness variation are determined as;

1. *Tempering process*: Improvement of furnace circulation to obtain homogenous temperature/hardness distribution.
2. *Induction hardening process*: Improvement of quenching efficiency.

After implementing proper actions, the hardness capability studies are conducted for verification of the selected actions

6.1. Tempering process

First study is planned to eliminate columnar stacking of the truck flywheel ring gear which restricts the circulation in tempering furnace. The parts are arranged with mismatching (by min 20 mm) position in order to improve air circulation

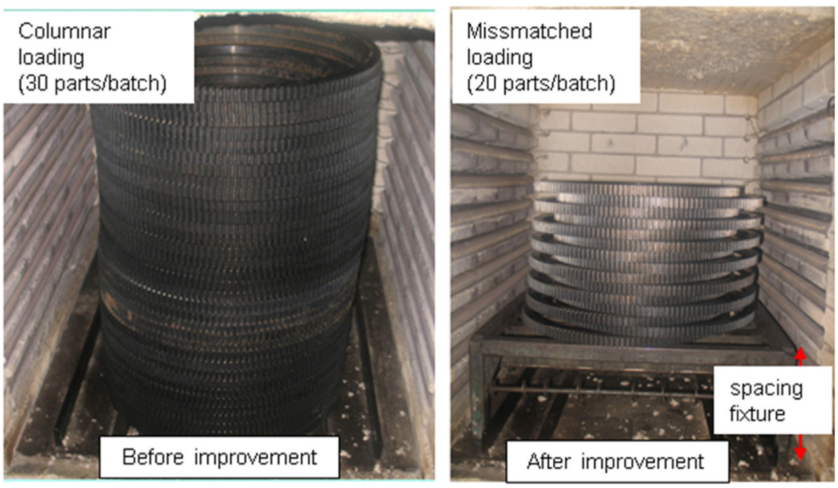

Fig. 12. Tempering process improvements in loading number and loading method.

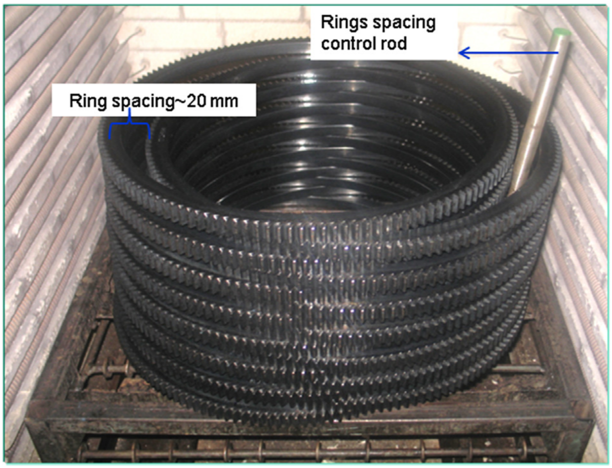

Fig. 13. Control method of proper loading.

during tempering process (Fig. 12). For error proofing and verification of proper loading of the gears, a practical control method with "control rod" is introduced to the process. When the operator loads the parts in the tempering furnace as batch, the control rod is deployed to maintain min 20 mm gap between parts (Fig. 13).

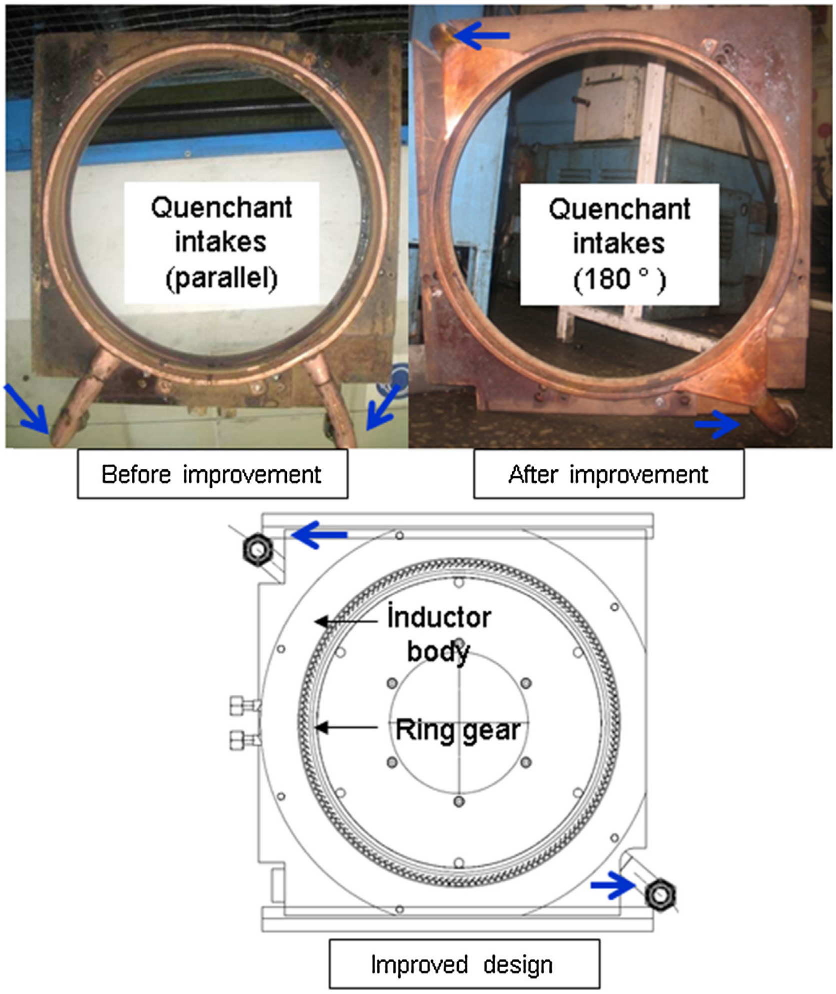

Fig. 14. Induction coil improvements of increasing quenching uniformity.

Second parameter to discuss is the part loading number which may intensify the columnar effect when loading from bottom to surface of the furnace with insufficient gap for circulation.

Related to the production volume of the truck flywheel production line; the tempering process is not a bottleneck operation and minimum loading number specified as minimum 20 parts/batch in tempering process specification.

To improve circulation, the loading part number for one charge was reduced from 30 part/batch to 20 part/batch for comparison.

In addition, the gears are set on special ''spacing fixture'' to improve circulation from the bottom of the charge (Fig. 12). The trials for temperature and time parameter are not planned at this step and agreed to be held if required.

The loading parameters and the equipments are specified for operators on process instructions.

6.2. Induction hardening process

Control of the quenching process of gears from high hardening temperatures ensures martensite microstructure. The cooling rate should be high enough to prevent formation of unwanted softer microstructures, such as pearlitic or bainitic ones; therefore, it is very important that in the development of new systems of induction hardening, quenching systems are designed properly [2].

As results issued induction process review; studies are carried out to improve quenching whole of the cross section of the truck flywheel ring gear homogenously.

For this purpose, the design of the ring gears inductor quenching ring and quenchant flows are reviewed. As mentioned before, from visual controls without rotating the part during quenching, areas with inadequate quenchant flow were matching with low hardness sections on truck flywheel ring gear. The main factor was the interference of quenchant jets with restriction of inner diameter > 470 mm inductor during quenching process.

In current inductor coil design, the quenchant intakes are located near to each other which may lead to interference in such large section. The goal of the study is to eliminate interference and maintain adequate quenchant flow to cross section of flywheel starter gear. To improve in large cross section of the coil quenchant flow, main quenchant intakes are located 180° to each other which were located at the same side and near to each other as shown in Fig. 14. Visual controls are conducted in the machine by canceling rotational table and eliminating of quenchant jet interference is confirmed.

6.3. Verification of improvements

Verification of the improvements in quenching and tempering processes, one batch with 20 parts was run. The parts are numbered and put into tempering furnace in sequence. After process the parts are measured at with 8 points as illustrated in Fig. 6a. The Anova analysis of the hardness measurements of the individual parts are reported in Fig. 15. In the graph the data before improvement is also added for comparison purpose.

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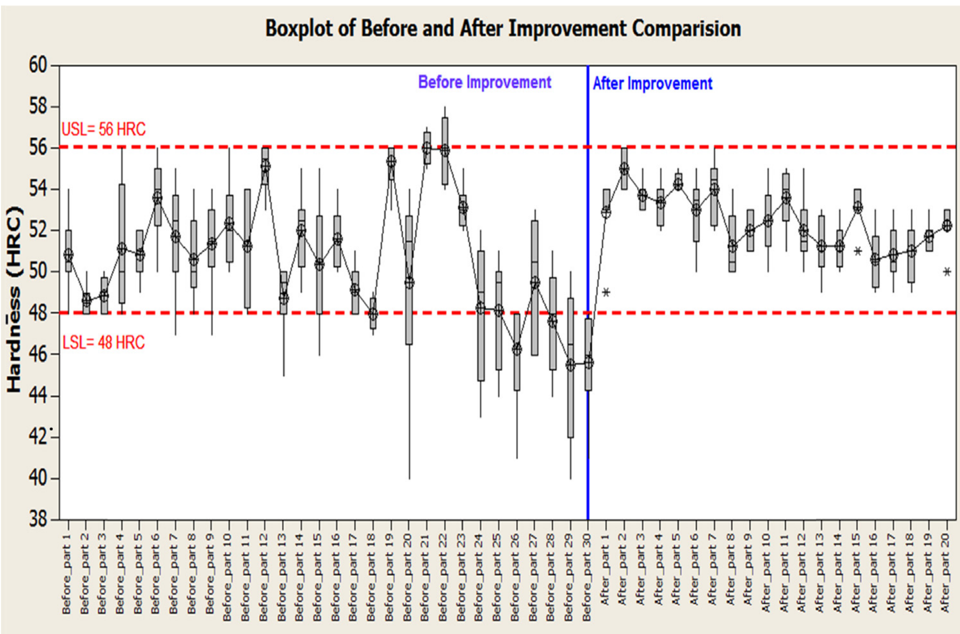
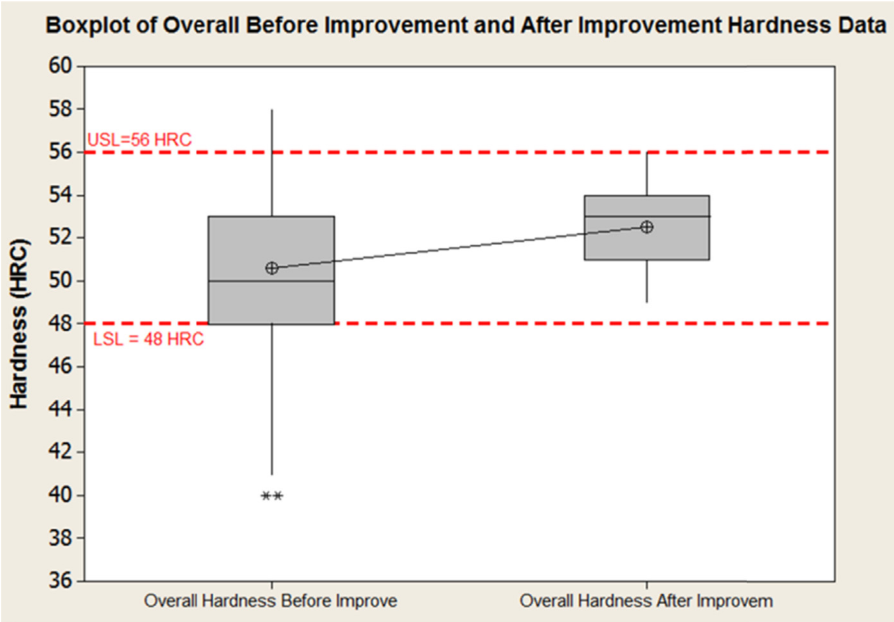


Fig. 15. Anova analysis of individual part to part and teeth to teeth hardness variation before and after improvement.



One-way ANOVA: Overall Hardness Before Improve; Overall Hardness After Improvem

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Source   DF       SS      MS      F      P
Factor    1   352,67  352,67  40,82  0,000
Error   398  3438,77    8,64
Total   399  3791,44

S = 2,939   R-Sq = 9,30%   R-Sq(adj) = 9,07%



Level                       N    Mean  StDev
Overall Hardness Before   240  50,571  3,526
Overall Hardness After I  160  52,487  1,716

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level                     ---+---------+---------+---------+------
Overall Hardness Before   (----*-----)
Overall Hardness After I                           (------*-----)
                          ---+---------+---------+---------+------
                          50,40     51,10     51,80     52,50

Pooled StDev = 2,939
```

Fig. 16. Before and after improvement overall hardness data comparison.

As a result; none of the points out of specification points is observed. Part to part and teeth to teeth variations (deviation) are decreased significantly. According to overall hardness data's comparison; before improvement average hardness is 50.57 HRC with 3.52 HRC standard deviation. After the improvement average hardness is near to nominal 52,487 HRC with 1.72 HRC standard deviation. (Fig. 16)

7. Summary/conclusions

Heavy duty engine's flywheel starter ring gears teeth profile is conventionally induction hardened and tempered in order to meet metallurgical aspects on blueprint. In this case, large section truck starter ring gears (with teeth root diameter 470 mm) the critical issue is to maintain stable hardness distribution part to part and also individual gears teeth profile.

In this paper, the factors effecting the hardness variations in induction hardening and subsequent tempering process was investigated to determine root causes. Two main improvement studies were conducted for permanent action:

1. In tempering process, the homogeneity of the air flow was determined as root cause diagnosis due to the trial results (Fig. 7). The truck starter ring gear furnace loading method and batch numbers were optimized to maintain homogenous temperature distribution (Figs. 12 and 13).
2. In induction hardening process, the root cause diagnosis was determined as the quench uniformity of whole cross section of large section gear. The diagnosis is verified with 2 step trial as discussed earlier (Fig. 10). Improvement of quenching homogeneity was established by improving the quenchant intake channels design in coil thus eliminate restriction of quenching in some sections (Fig. 14).

After implementing these actions the hardness capability studies are conducted for verification of the selected actions by anova analysis of before and after status. After improvement the average hardness was optimized to average of 52.487 HRC with 1.72 HRC as reported in Fig. 16 (with 50% variation reduction). By ensuring capable process, hardness measurement frequencies are reduced from 100% to 1/batch (1/20 part) and the number of hardness measurement points are reduced from 8 to 3.

Achievements of flywheel starter ring gear hardness variation optimization study are:

1. Scrap costs are eliminated due to hardness.
2. Excessive measurement frequencies are eliminated due to hardness variations and thus labor efficiencies improved.
3. No failure on engine in low mileages due to out of specification in hardness.

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